NARROW-BAND HYBRID PULSED LASER/EMAT SYSTEM FOR NON-CONTACT ULTRASONIC INSPECTION USING ANGLED SHEAR WAVES

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INTRODUCTION

Conventional ultrasonic testing (UT) using angled shear waves to locate and size potentially critical cracks and flaws in power generation and refinery equipment has become a widely utilized industrial tool. Because this technique uses piezoelectric transducers it requires intimate surface contact and fluid couplants. Therefore, conventional UT has the important drawback that it is difficult to use on surfaces at elevated temperature and, as a result, may require costly plant shut downs to implement. The development of non-contact techniques for angled shear wave UT would represent a significant improvement in the ability to test hot vessels and pipes.

One alternative to conventional, contact UT methods, which has been investigated, is laser ultrasonic testing. In this technique laser beams are used both to generate and detect ultrasonic signals. If such a system could be implemented practically, it would provide the means for completely non-contact and remote ultrasonic testing. Indeed, a pulsed laser can be used efficiently as a generator of vertically polarized, angled shear waves if the power density at the surface causes only rapid thermal expansion (thermoelastic generation). The directivity pattern of thermoelastic generation is dominated by a 30 degree conical lobe [1,2]. On the other hand, unfortunately, laser interferometer systems are generally poor receivers of shear wave displacements. Furthermore, the performance of a laser receiver can be strongly dependent upon the nature of the surface finish over the inspection region.

An alternative to an entirely laser-based ultrasonic inspection system is one in which the problematic laser receiver is replaced with an EMAT (Electro-Magnetic Acoustic Transducer). The resulting pulsed laser/EMAT hybrid system is still technically non-contact, but no longer remote. The EMAT needs to be placed in close proximity to the vessel surface but requires no couplants or special surface preparation, and can be made to operate at elevated temperatures. The EMAT, which is not an efficient generator of ultrasound, is an excellent receiver for angled shear waves. The pulsed laser/EMAT system is, therefore, a near ideal combination for angled shear wave testing without surface contact.

An EMAT is basically a meandering coil of wire placed within an externally applied (biasing) magnetic field which is normally supplied by a permanent magnet. When placed near the surface of an electrically conductive material, the EMAT's coil can be used to generate or receive ultrasound. It can be electrically driven to induce vibrations or used as a near-field antenna receiving the electromagnetic disturbances caused by propagating ultrasonic waves.

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EMATs have been well characterized [3-6] and function on the principle of Lorentz interaction [7] with an added magnetostrictive effect in ferromagnetic materials[8].

EMATs have been used for years in both pulse/echo and transmit/receive configurations. They have proven useful in the measurement of stresses in steel sheets [9,10] and in railroad rails where their non-contact nature may allow them to be used as part of an on-line maintenance device [11,12]. Corrosion and crack location in plates have also been accomplished using EMATs that generate vertically and horizontally polarized, angled shear waves [13]. Broad-band laser/EMAT pairs have been demonstrated for applications such as aircraft lap joint testing [14], Lamb-wave corrosion location [15] and in-process weld inspection [16].

The novelty of the present work is that the pulsed laser/EMAT system is employed in a narrow frequency band or resonant configuration. The EMAT is part of a tunable resonant circuit which is composed of the EMAT coil itself and an adjustable shunt capacitor. To match the frequency response of the tuned EMAT, a laser system is implemented which can be pulsed in rapid succession at the EMAT's resonant frequency. This configuration is unlike those described previously in which the EMAT was forced to be broad-banded to match the ultrasonic spectrum generated by a single laser pulse [17].

In addition to the enhanced detection sensitivity resulting from matching of the laser source's and EMAT receiver's frequency characteristics, the present, narrow-band laser/EMAT method has some other significant advantages. For example, thermoelastic generation, which is required for strong angled shear wave generation (30° lobes), can only occur at relatively low laser pulse energy densities. Above some energy density threshold, the event becomes ablative, scarring the surface. Ablation causes the additional laser energy to be coupled primarily into the normal longitudinal wave (with lambertian directivity) and the Rayleigh wave (SAW) at the expense of the shear wave. This energy threshold, which is lower for steel than it is for aluminum, limits how much energy can be coupled from a single laser pulse to the angled shear wave mode. Working below this energy threshold precludes the possibility of significant material surface damage. In the present system up to ten laser pulses at energies below the ablation threshold illuminate, in rapid succession, a single spot on the test piece surface. Consequently, the usable shear wave energy in the material is increased over the maximum that a single pulse could provide.

Another advantage of the narrow-band system stems from the fact that the angle at which the meander line EMAT is most sensitive to ultrasonic waves is proportional to the wavelength, and therefore frequency, of the waves. An angled shear wave arriving at the surface will have a surface wavelength that is greater than the actual wavelength by a factor proportional to the sine of the angle of incidence. When this surface or projected wavelength matches twice the EMAT conductor spacing a current is induced in the coil. The characteristic equation for a meander line EMAT is

$$\sin\theta = \frac{v}{2bf} . \qquad (1)$$

Here v and f are the ultrasonic wave's velocity and frequency and b is the center spacing between the conductors on the meander line EMAT. For a given meander line coil receiving an ultrasonic wave, the angle of maximum sensitivity, $\pm\theta$, will be different for different frequency components. If a resonant EMAT is made by adding a shunt capacitor or filtering electronics, then only a particular frequency, and therefore a particular angle of incidence, is selected. Thus, by tuning the EMAT resonance the device can be adjusted to receive waves from a specific angle. When using the EMAT to receive ultrasound from a thermoelastic pulsed laser source θ is tuned to 30°.

ANGLED SHEAR WAVE GENERATION AND DETECTION

Single Pulse Laser Source/EMAT Detection of a Cut in Plates

To demonstrate the compatibility of the pulsed laser and the meander line EMAT for angled shear wave ultrasonic testing two plate specimens were created with one third through thickness saw cuts. The test configuration for both specimens is shown in Figure 1a. The pulsed laser (Nd:YAG, 1.06 μm, delivering ~6 mJ in 9 ns) labeled as "I.R.", and EMAT were used side-by-side. Using a cylindrical lens (not shown) the laser beam was focused to a line source running parallel to the conductor lines of the EMAT (into the plane of the page) on the metal's surface. Because of symmetry, the pulsed laser/EMAT combination has "front" and "back" lobes of sensitivity.

The first of these test specimens was an aluminum plate 37 mm thick. Shown in Figure 1b is the EMAT signal, an average of ten single laser firings, for the indicated "front lobe" path. The retroreflected signal from the cut is seen at 30 μs. The Rayleigh wave from the generation event is visible in the first 10 μs of the trace. Note that the frequency selectivity of the resonant meander line EMAT strongly filters out the Rayleigh wave arrival. Such a large wave arrival could saturate the amplifier of a broad-banded EMAT, masking early ultrasonic signals.

Similarly, a steel plate, 22 mm thick, with a one third through thickness cut was tested in an identical configuration. Figure 1c shows the arrangement and the resultant EMAT signal averaged over ten single laser firings. In this figure the retroreflected signal from the cut is visible at 20 μs. Note the deterioration of the signal-to-noise ratio of the signal from the steel specimen (Figure 1c) relative to the aluminum specimen (Figure 1b) in spite of its smaller thickness. This deterioration is a result of steel's higher ultrasonic attenuation and lower electrical conductance affecting the EMAT's conversion efficiency.

NARROW-BAND LASER TECHNIQUE

The pulsed laser/EMAT system, as employed above, used only a single laser pulse but was capable of detecting one third through thickness, opposite side, cuts. However, to detect small (real) cracks in steel, it was necessary to increase the signal-to-noise ratio of the system. A single laser pulse generates a broad spectrum of ultrasound resulting in a spectral mismatch between the ultrasonic generator and receiver (the resonant EMAT). Broadening the EMAT response to match the laser pulse spectrum was one possibility but had several disadvantages including loss of the adjustable angular selectivity and Rayleigh wave signal suppression. Instead, it was more useful to modify the spectrum of the laser generated ultrasonic signal by rapidly pulsing the laser source (multipulsing) to match the resonance of the EMAT. Multipulsing allows the ultrasonic spectrum to be shaped, placing the fundamental frequency at a pulse repetition rate chosen to match the EMAT's resonance. Multipulsing had the added advantage that it allowed more shear wave energy to be introduced into the metal than could be thermoelastically generated with a single pulse. The system operated at laser power densities below the ablation threshold for optimal shear wave production and minimal surface damage.

The generation of the I.R. pulse train required to create the narrow-band ultrasound can be accomplished in a number of ways. In the past researchers have used mode locked lasers [18] and single pulsed laser/optical delay (White cell) combination [19] to generate the necessary pulse trains. However since the EMAT is typically limited to less than 5 MHz operation frequency (because of stand-off issues) the mode locked and White cell laser methods become difficult to implement since long optical delays are needed.

In this work a new ten cavity laser system, show schematically in Figure 2a, was used to generate the required periodic pulse train. This multi-element laser was composed of ten Q-switched Nd:YAG cavities with a common power supply and timing electronics [20]. The timing circuit allowed the cavities to be fired with any desired delay. Turning mirrors were used to direct the I.R. light pulses through a cylindrical lens to the test specimen. This arrangement allowed each cavity's pulse to be focused to a line at a fixed distance adjacent to the EMAT on

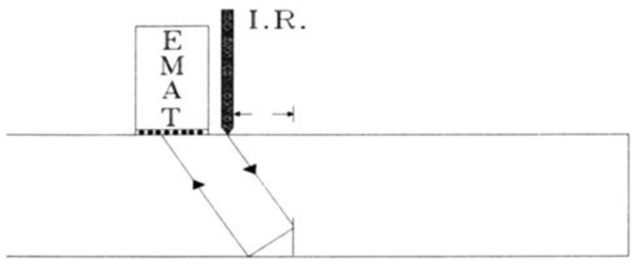

Figure 1a. The test configuration for single pulse excitation in an aluminum plate and a steel plate with one third through thickness cuts.

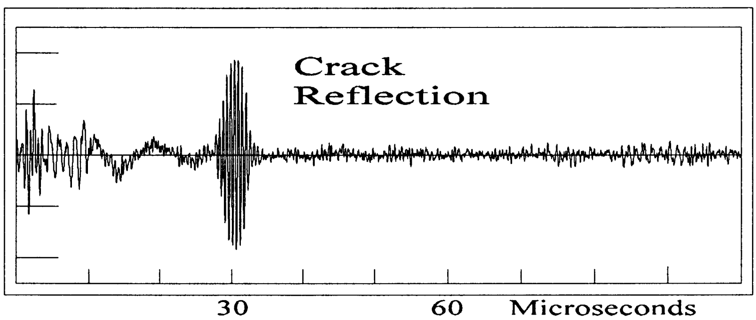

Figure 1b. The EMAT detected cut reflected signal (averaged ten times) in a 37 mm thick aluminum plate.

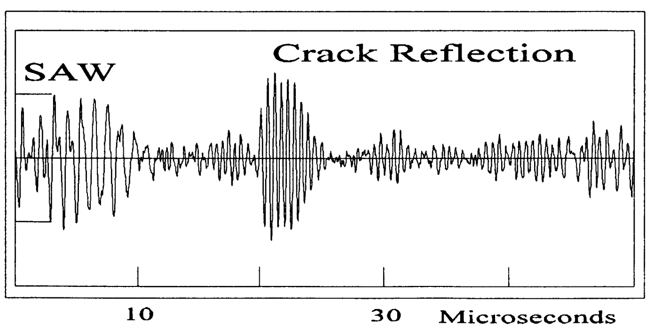

Figure 1c. The EMAT detected cut reflected signal (averaged ten times) in a 22 mm thick steel plate.

the metal's surface. The photodiode detected output of the multiple cavity system is shown in Figure 2b for the case when all ten cavities are pulsed at 500 ns separation. Shown in Figure 2c is the power spectrum of the photodiode signal showing a fundamental frequency at 2 MHz.

Test Specimen Examination Using The Hybrid System

Shown in Figure 3a, an aluminum plate with a "penny-shaped" cut was tested to demonstrate the improved sensitivity of the narrow-band laser technique. The penny-shaped cut (insert Figure 3a) was 3 mm deep, 25 mm end-to-end and 0.7 mm wide. In this illustration of the test configuration "I.R." indicates the spot where all of the laser pulses were incident. Also indicated is the expected retroreflected ultrasonic path from the penny-shaped cut to the EMAT. EMAT response to ultrasound generated by I.R. pulse trains of one, three, five and seven pulses is also shown (Figure 3b). With the increased number of pulses the cut reflection signal became increasingly greater than the surrounding noise. Figure 3c shows the spectra of the EMAT time signals which demonstrate that adding additional pulses increased the frequency content at the pulse repetition rate.

Examination Of A Plate Weld Using The Narrow-Band Pulse Laser/Emat System

Finally, the pulsed laser/EMAT hybrid system was used to inspect a steel plate weld specimen to simulate the testing of a reaction vessel. The specimen, manufactured by Sonaspection, is illustrated in Figure 4a. It was 30 cm square and 2 cm thick, and had been inspected using conventional UT. The results of the conventional UT documented the location of three defects, two root cracks and a porosity region, in the specimen. A translation stage was used to scan the weld specimen in front of the laser/EMAT system. Figure 4b shows the EMAT signals from four areas of interest adjacent to the good weld section, root crack #1, root crack #2, and the porosity. The first 15 μs of the traces reveal a mix of Rayleigh wave (SAW) arrivals from both the direct (generation site to EMAT) and weld reflected paths. The defects are discernable and can be sized by moving the pulse laser/EMAT system back and forth relative to the weld.

CONCLUSION

The multiple cavity pulsed laser/meander line EMAT system has been demonstrated in a number of experimental cases. The narrow-band EMAT has been shown to be well suited for detection of thermoelastically generated shear waves. The system was also used to perform angled shear wave ultrasonic inspection on a number of test specimen types. Specimens included aluminum and steel plates with one third through thickness saw cuts to mimic cracks, and a steel weld specimen to imitate a reaction vessel wall. The pulsed laser/EMAT system was capable of detecting opposite side cuts in single pulse mode but required signal averaging. Furthermore it was not able to detect same side cuts or real cracks. The multiple pulse technique was then successfully used to boost the signal-to-noise ratio of the system by narrowing the ultrasonic spectrum and concentrating it at the resonant frequency to the narrow-band EMAT. This technique made it possible to perform ultrasonic inspection, without contact, of not only one third through thickness cuts but also small penny cuts in aluminum and real cracks in a steel plate weld specimen.

ACKNOWLEDGEMENTS

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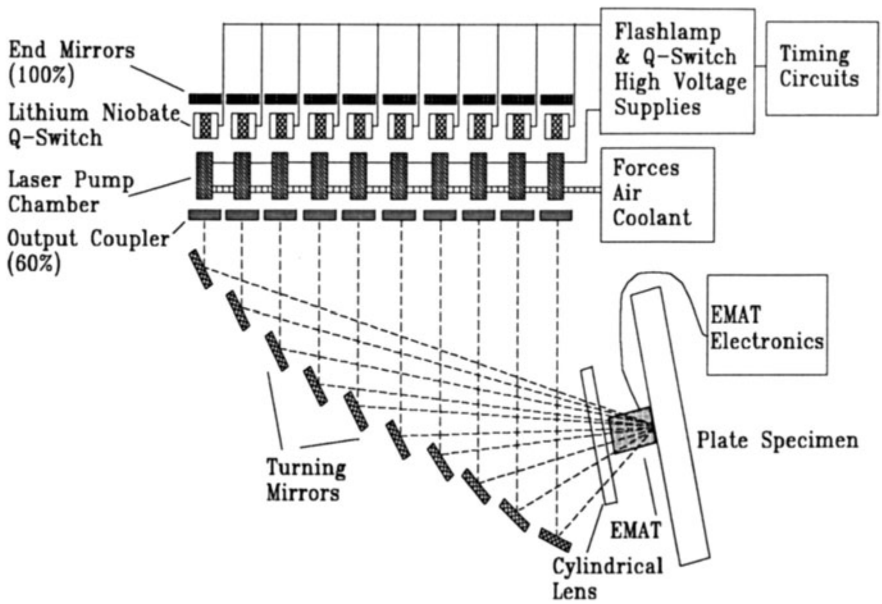

Figure 2a. Ten cavity Nd:YAG laser system used to generate narrow-band ultrasound.

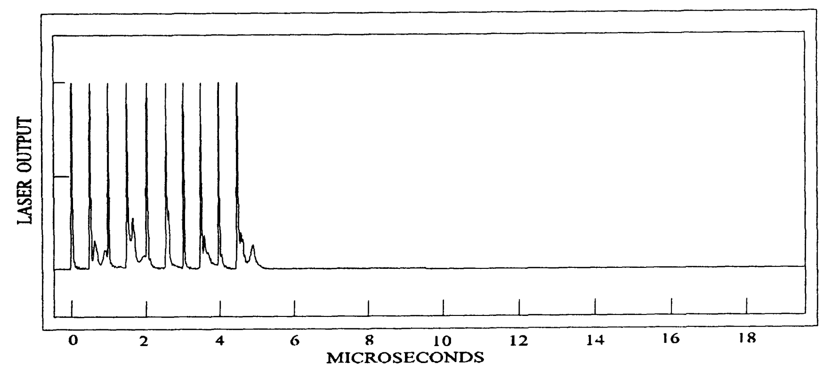

Figure 2b. The optical signal from the multiple cavity laser system with all ten cavities firing.

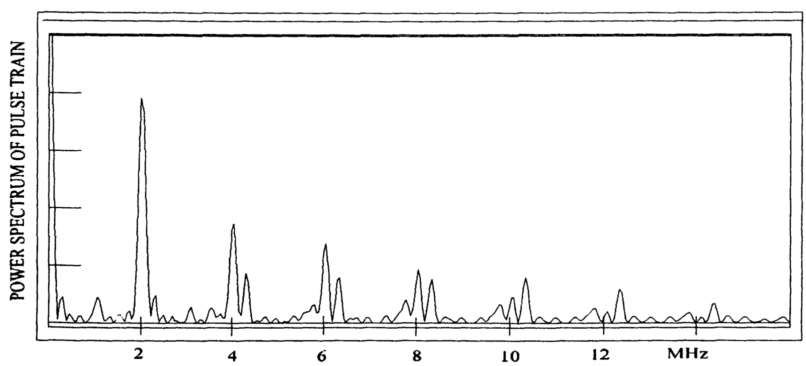

Figure 2c. The power spectrum of the optical pulse train shown in Figure 2b.

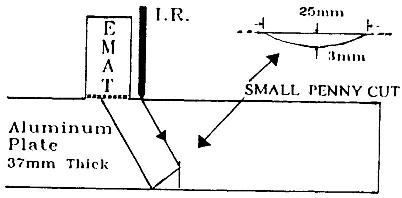

Figure 3a. Multiple pulse excitation in an aluminum plate containing a penny cut.

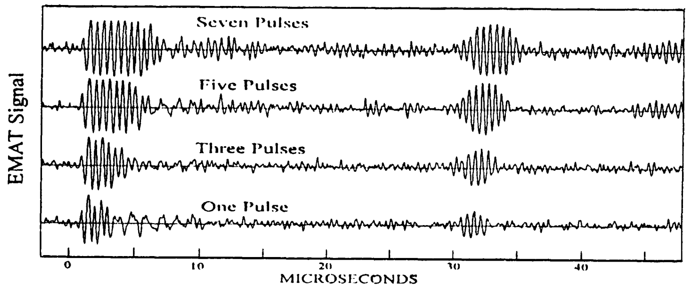

Figure 3b. EMAT signals shown for one, three, five and seven pulse sequences from the multiple cavity laser system.

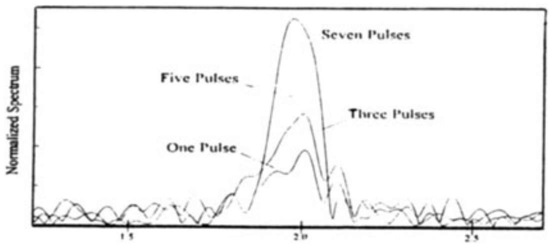

Figure 3c. The normalized spectra of the time signals shown in Figure 3b.

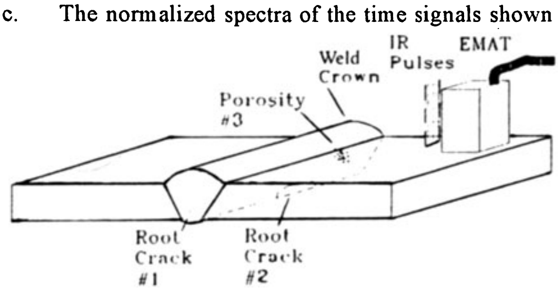

Figure 4a. Weld inspection using the ten cavity pulsed laser/EMAT system.

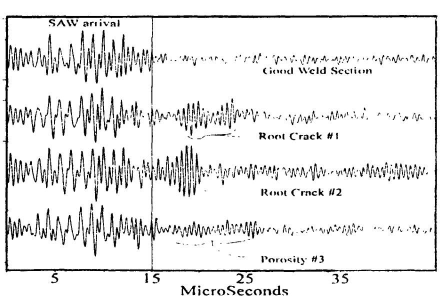

Figure 4b. Signal traces showing each of the three defect areas as well as a good weld section.

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